SHALLOW WATER STATION KEEPING OF AUVS USING MULTI-SENSOR FUSION FOR WAVE DISTURBANCE PREDICTION AND COMPENSATION

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Abstract - An important capability for Autonomous Underwater Vehicles (AUVs) is station keeping. Station keeping is the ability of a vehicle to maintain position and orientation with regard to a reference object. In shallow water this mission most likely will be disrupted by the large wave induced hydrodynamic forces acting on the vehicle. To counter this problem, knowledge of these wave induced disturbances is critical to allow for the design of a control system that will enable the vehicle to accurately navigate and position itself.

The ability to develop a so called "predictive" control strategy for underwater vehicles is limited by the methods available to measure and predict the wave induced disturbances. Surface vessels may employ remote sensors such as acoustic probes, lasers or short wavelength radar to determine future disturbances, but this remote sensing is not feasible in a low cost underwater vehicle. AUV control system design is limited to the use of on board sensors for disturbance prediction.

In this paper, we present the design of a Sliding Mode Controller (SMC) that employs multisensor data fusion for wave disturbance prediction/estimation. Using data obtained from the vehicle's Doppler, Acoustic Doppler Velocimeter (ADV) and motion package, a dynamic filter is developed that will fuse the information from the various sensors and provide the controller with an estimate of the wave induced disturbance, thus allowing the vehicle to station keep in both heading and position with far greater accuracy.

I. INTRODUCTION

For an Autonomous Underwater Vehicle to operate with a high degree of reliability, disturbances and their effects on the AUV must be modeled mathematically with an adequate degree of accuracy. The main source of the dynamic disturbances encountered by underwater vehicles in very shallow water are wave and current induced. These disturbance forces arise from buoyant and inertial effects due to ocean wave kinematics.

In this paper, we will show how the bulk directionality of the seaway may be estimated using on board sensors. This estimated direction provides the necessary heading command to allow the vehicle to maintain an optimal orientation to an object to which the vehicle is positioning. Second, a sliding mode controller is cast which embodies the wave disturbances. A Kalman Filter is used to fuse sensor measurements, and provide an estimate of the wave states based on measurements obtained from the sensor suite. The controller will use the fluid velocity estimates to cancel the wave induced disturbances thereby improving the vehicle's ability to maintain position.

Finally, through simulation, we apply the developed filter and controller to the NPS "PHOENIX" AUV and demonstrate its ability to hold position while subjected to actual shallow water waves.

II. SEAWAY DIRECTION ESTIMATION

The cross-spectra of a tri-directional current meter yield low resolution directional wave information equivalent to that obtained from measurements of commonly used surface-following heave-pitch-roll buoys [1, 2, 3]. The normalized co-spectra of the vertical (z) velocity component w, and the horizontal (x, y) velocity components u and v yield the lowest four Fourier moments of the directional distribution (spreading function) of wave energy $S(q) \equiv E(f,q)/E(f)$, given by,

$$a_1(f) = \frac{\mathrm{Im}(C_{wu}(f))}{\left[C_{ww}(f)\left[C_{uu}(f)+C_{vv}(f)\right]\right]^{1/2}}, \qquad (1)$$

$$b_1(f) = \frac{\mathrm{Im}(C_{wv}(f))}{\left[C_{ww}(f)\left[C_{uu}(f)+C_{vv}(f)\right]\right]^{1/2}}, \qquad (2)$$

$$a_2(f) = \frac{C_{uu}(f)-C_{vv}(f)}{C_{uu}(f)+C_{vv}(f)}, \qquad (3)$$

$$b_2(f) = \frac{2\,\mathrm{Re}(C_{uv}(f))}{C_{uu}(f)+C_{vv}(f)}, \qquad (4)$$

where ***C(f)*** is the spectral matrix of the velocity components u, v, w. Since the direction, q, is referenced to the navigation frame (N-E-D), vehicle borne sensor measurements must be transformed prior to use. It is interesting to note that the estimates of these directional moments are insensitive to errors, so long as the errors are the same on all measurement axes of the sensors, which is typical with oceanographic sensors installed on AUVs.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2005**	2. REPORT TYPE	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **SHALLOW WATER STATION KEEPING OF AUVS USING MULTI-SENSOR FUSION FOR WAVE DISTURBANCE PREDICTION AND COMPENSATION**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Naval Postgraduate School,Center for AUV Research,Monterey,CA,93943-5000**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
An important capability for Autonomous Underwater Vehicles (AUVs) is station keeping. Station keeping is the ability of a vehicle to maintain position and orientation with regard to a reference object. In shallow water this mission most likely will be disrupted by the large wave induced hydrodynamic forces acting on the vehicle. To counter this problem, knowledge of these wave induced disturbances is critical to allow for the design of a control system that will enable the vehicle to accurately navigate and position itself. The ability to develop a so called "predictive" control strategy for underwater vehicles is limited by the methods available to measure and predict the wave induced disturbances. Surface vessels may employ remote sensors such as acoustic probes, lasers or short wavelength radar to determine future disturbances, but this remote sensing is not feasible in a low cost underwater vehicle. AUV control system design is limited to the use of on board sensors for disturbance prediction. In this paper, we present the design of a Sliding Mode Controller (SMC) that employs multisensor data fusion for wave disturbance prediction/estimation. Using data obtained from the vehicle’s Doppler, Acoustic Doppler Velocimeter (ADV) and motion package, a dynamic filter is developed that will fuse the information from the various sensors and provide the controller with an estimate of the wave induced disturbance, thus allowing the vehicle to station keep in both heading and position with far greater accuracy.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**5**	

For narrow $S(\theta)$, a mean propagation direction θ_m and a root-mean-square measure of the directional spreading energy σ_θ can be defined in terms of the first-order and second-order Fourier moments a_1, b_1, a_2 and b_2 [4]:

$$\theta_m = \tan^{-1}\left(\frac{b_1}{a_1}\right) \tag{5}$$

$$\sigma_\theta^2 = 2\left[1 - \left[a_1 \cos(\theta_m) + b_1 \sin(\theta_m)\right]\right] \tag{6}$$

$$\theta_m = \frac{1}{2}\tan^{-1}\left(\frac{b_2}{a_2}\right) \tag{7}$$

$$\sigma_\theta^2 = \frac{1}{2}\left[1 - \left[a_2 \cos(2\theta_m) + b_2 \sin(2\theta_m)\right]\right]. \tag{8}$$

The resulting directions and variances, from (5)-(8), are for each frequency component of the wave. To use this information as a heading command, a single bulk fluid direction must be found. Bulk Fourier moments, weighted by the energy density of the wave field,

$$\begin{bmatrix} a_1^b \\ b_1^b \\ a_2^b \\ b_2^b \end{bmatrix} = \frac{1}{E^b}\int_{f_l}^{f_u} E(f) \begin{bmatrix} a_1(f) \\ b_1(f) \\ a_2(f) \\ b_2(f) \end{bmatrix} df \tag{9}$$

with E^b the swell variance

$$E^b = \int_{f_l}^{f_u} E(f)df \ , \tag{10}$$

may be substituted into (5)-(8) to yield a bulk fluid direction and variance. It is this bulk fluid direction that is used as the heading command.

III. VEHICLE SURGE MODEL

Much of the research in the past has dealt with deep water use of AUVs. In this environment, the influence of wave induced forces is minimal as long as the vehicle is not operating too close to the surface. In a shallow water environment, the ability of a vehicle to escape these wave induced forces is impossible since these forces exist throughout the water column. Therefore, to properly design a surge controller it is necessary to begin with as accurate a model of the vehicle surge dynamics as possible.

The equations of motion (EOM) based on constant hydrodynamic coefficients for an underwater vehicle are well known and documented in the literature, reference [5] being just one example. In general, the hydrodynamic forces on a submerged vehicle depend on the relative velocity and acceleration between the water particles and the vehicle. The general case of longitudinal (surge) motion in the *u*-direction written in compact form is given by,

$$(m + X_{\dot u})\dot u_r + X_{uu} u_r |u_r| = F_{prop}(t)\ , \tag{11}$$

where

$$u_r = (u_g - U_{fluid})\ , \tag{12}$$

and $F_{prop}(t)$ represents the propulsion force. The propulsion force can be modeled as

$$\dot F_{prop} = \frac{-1}{\tau} X_{prop} + \frac{\beta}{\tau} n|n|\ , \tag{13}$$

where τ and β represent a time constant and a thrust parameter, respectively. Combining (11) and (13) and adding the kinematic relation for a vehicle constrained to longitudinal or surge motion, the following system of equations is developed,

$$\begin{aligned} \dot X &= u_r + U_f \\ \dot u_r &= \alpha u_r |u_r| + F_{prop} \\ \dot F_{prop} &= \frac{-1}{\tau}F + \frac{\beta}{\tau} n|n| \end{aligned} \ , \tag{14}$$

where the steady state current and oscillatory velocity caused by waves are added directly to the kinematic equation since relative velocities are used in (11). It should be pointed out, that in the form used in (14), F is a generalized force with units the same as an acceleration.

With the three state surge model (14) developed, an accurate determination of the parameters α, β, and τ is needed. As Marco [6] has pointed out, using system identification, it is possible to obtain these values. Since the time of Marco's experiments in [6], the PHOENIX AUV has had its propulsion system upgraded, to include brushless DC motors for propulsion, increased diameter/pitch propellers and ducted shrouds. From at-sea trials, the vehicle, as a result of these system upgrades, is now capable of approximately 3.5-knots (~1.8 m/s) at 525 revolutions per minute. Based on these upgrades, the values for α, β, and τ are

$$\begin{aligned} \alpha &= -4.036 \text{ m}^{-1} \\ \beta &= 1.034 \text{ m/rev}^2 \\ \tau &= 1.15 \text{ s} \end{aligned} \ , \tag{15}$$

which will be used throughout the remaining design and simulation.

IV. CONTROLLER DESIGN

Beginning with (14), a sliding mode controller was formulated using standard SMC techniques. The sliding surface s was defined as a function of the position error,

$$s = \left(\frac{d}{dt} + \lambda\right)^2 \left(X - X_{com}\right), \tag{16}$$

and the time derivative of s was defined as

$$\dot s = -\eta sat(s/\phi)\ , \tag{17}$$

with η, λ and ϕ controller tuning parameters. Taking the time derivative of (16) and equating it to (17), the control input may be determined.

$$n\left|n\right| = \frac{t}{b}\begin{bmatrix} \dot{s} - 2au_r\left[au_r\left|u_r\right| + F\right]sign(u_r) + \\ \frac{F}{t} - \ddot{U}_f + \dddot{X}_{com} - 2l(au_r\left|u_r\right| + F + \\ \dot{U}_f - \ddot{X}_{com}) - l^2(u_r + U_f - \dot{X}_{com}) \end{bmatrix} \qquad (18)$$

Using the signed square root of (18), the commanded control input is found. A detailed description of this controller design approach may be found in [7]. In (18), u_r represents relative velocity expressed in the vehicle frame, and U_f represents fluid velocity expressed in the vehicle navigation frame.

To display how well this controller is capable of performing, consider the simple case of a monochromatic sine wave disturbance. When knowledge of the wave disturbance is embedded in the control system design, perfect cancellation of the wave disturbance effects on station keeping may be obtained. The simulated response of the PHOENIX, initially at five meters and closing to a commanded range of 0.5 meters, is displayed in Fig. (1). The results in Fig. 1 are for demonstration purposes only, and we do not expect to get perfect cancellation of the wave disturbances since exact measurement of each wave disturbance component, i.e. $U_f, \dot{U}_f$ *and* $\ddot{U}_f$, is not possible.

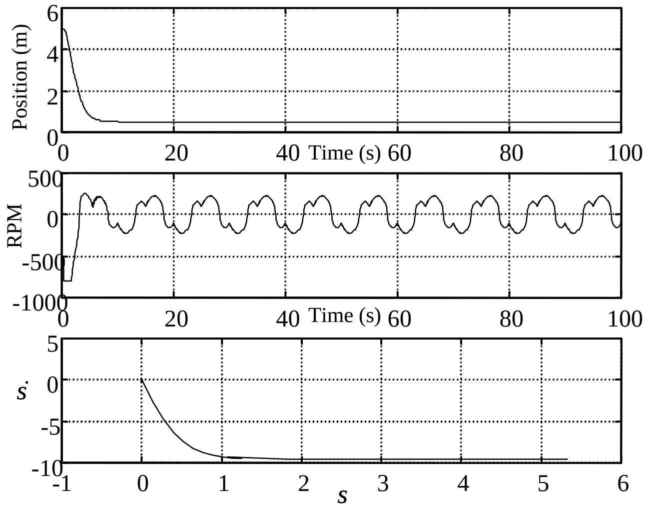


Fig. 1 Example Disturbance Cancellation, top to bottom respectively, position vs. time, propeller RPM vs. time, and a phase plane plot of the sliding surface

V. FUSION FILTER

As indicated in (18) and demonstrated by the simulation of the previous section, the controller requires knowledge of the fluid velocity and its first and second derivatives, expressed in the vehicle navigation frame, to cancel the wave induced disturbances. Since these quantities are not all measurable, they must be some how obtained from the sensor measurements which are available from the AUV. To estimate these values, a Kalman based fusion filter, driven by velocity measurements, was developed.

Prior to use in the estimation filter, the sensor measurements must be processed through a fusion transformation matrix (FTM). This matrix will fuse ground speed from the Doppler, relative water speed from the ADV, and vehicle attitude (pitch, heading and roll orientation) from the motion package, to produce the fluid velocity, expressed in the navigation frame, necessary to drive the estimation filter. The fusion transformation matrix has the form

$$FTM\ (f,q,y) = [T^{-1}(f,q,y),\ -T^{-1}(f,q,y)], \qquad (19)$$

where $T^{-1}(f,q,y) \in \Re^{3x3}$ is the inverse Euler transformation [8]. The resulting measurement transformation has the form

$$\begin{bmatrix} U_f \\ V_f \\ W_f \end{bmatrix} = FTM\ (f,q,y)\begin{bmatrix} u_g \\ v_g \\ w_g \\ u_r \\ v_r \\ w_r \end{bmatrix}, \qquad (20)$$

where the first three measurements, u_g, v_g, w_g, are obtained from the Doppler, and the second three measurements are obtained from the ADV.

The estimation filter was designed assuming that the signal could be represented by a fifth-order dynamic system, three states used for $U_f, \dot{U}_f, \ddot{U}_f$, and second-order wave dynamics, of the form

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} . \qquad (21)$$

The ***A, B*** and ***C*** matrices have the form

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -w_o^2 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 \end{bmatrix}^T , \qquad (22)$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

and the input u is white noise. The parameter w_o is the fundamental frequency of the wave field found by the frequency methods used during the directionality estimation outline in Section II.

Using this dynamic system and appropriate values of Q and R to properly weight the model uncertainty and system noise, a filter was developed that will estimate the required values, necessary for the controller [9]. To determine the accuracy of the filter, realistic sensor records containing noise and measurement uncertainty were generated. These records were used to tune the filter gains, and determine the accuracy of the filter estimates. Fig. (2) shows this in detail.. As can be seen, the fifth-order filter

provides acceptable tracking and smoothing of the required signals needed in the controller.

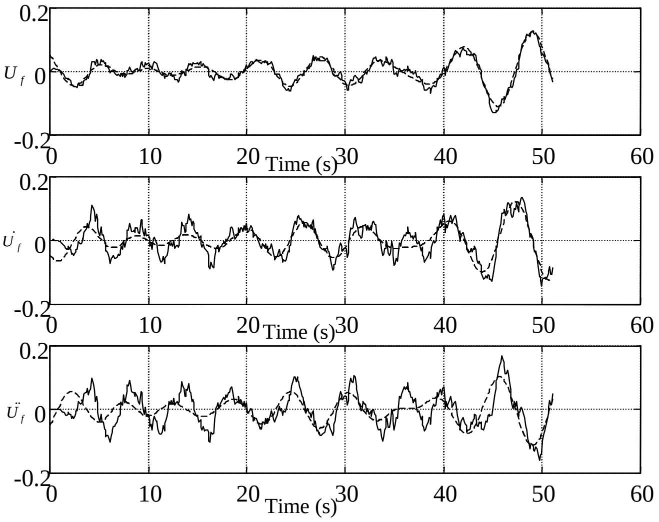


Fig. 2 Fusion Filter Results, top to bottom , surge velocity, first and second derivatives, respectively (dashed lines), and the filter estimates (solid lines) vs. time

VI. RESULTS

Prior to implementation of the fusion filter, we conducted several simulations to determine the performance that could be obtained from the controller with and without all disturbance components available. The disturbance components in these simulations were assumed to be measurable and included noise. The results of this comparison are shown in Fig. 3.

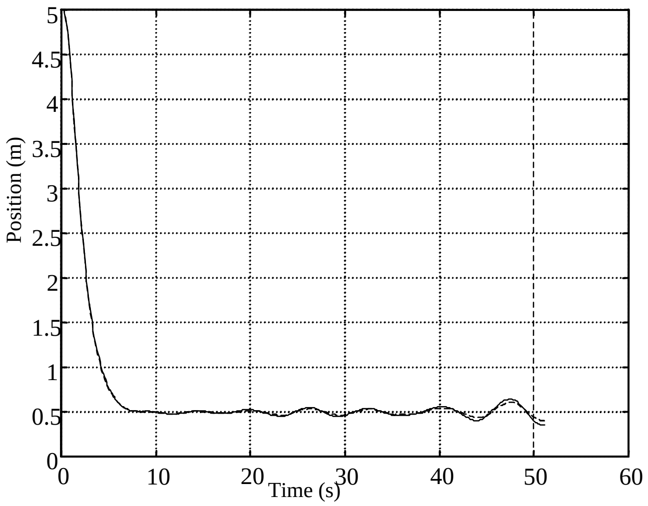
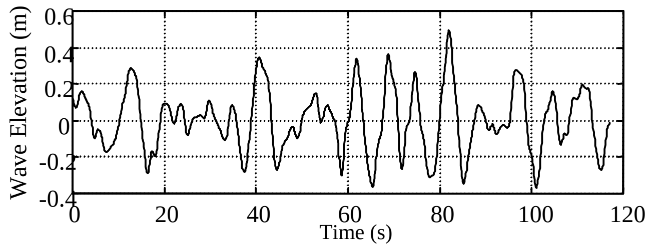


Fig. 3 Controller Performance Comparison, for a controller that uses all the disturbance components (dashed line), and a controller that uses only fluid velocity for disturbance cancellation (solid line).

As can be seen in Fig. 3, the stationkeeping improvements associated with including all components as opposed to including only the fluid velocity component is very small. In each case, the propulsion system response was within the vehicle's capability, but was extremely oscillatory at a high frequency due to the sensor noise.

As a result of the comparisons, it was determined that by using only the fluid velocity measurements, significant improvement with regard to positioning may be achieved, but that the fusion filter was needed to filter the noise and improve the high frequency response of the propulsion system.

The final simulations involved implementing the combined fusion filter/controller subject to real wave data. The data used in the simulation was obtained in Monterey Bay, CA on April 9th 1998. The Bay was classified as a force 3 on the Beaufort Scale, with a significant wave height of approximately 0.6-meters. A portion of a surface elevation record, obtained from a Datawell® Directional Waverider buoy, and a portion of the surge velocity record, obtained from a velocity array taken at a depth of 20 feet (6.1 meters) in 45 feet (13.7 meters) of water, is shown in Fig. 4. As seen in the velocity plot, there is a steady current of approximately 0.2 m/s (0.4 kts). This current is caused by the bottom topography associated with Monterey Bay.



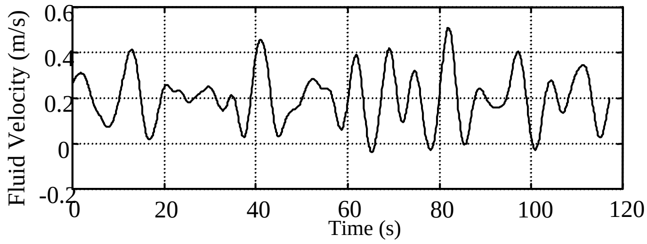


Fig. 4 Sample Wave Elevation and Fluid Velocity Record, upper plot wave elevation, lower plot fluid velocity

The combined filter/controller results, using the real wave data described above, are shown in Fig. 5. The initial conditions and commanded position are identical to the values used in the example disturbance cancellation simulation of Fig. 1.

As can be seen, the vehicle response using disturbance compensation, is maintained around the commanded value of 0.5 meters, with a standard deviation of 8.5 cm, and the propeller response is within propulsion system capabilities, without too much oscillation. The small offset from the commanded position is due to the influence of the boundary layer, used to reduce controller chattering, in the sliding mode design.

The vehicle response, without disturbance compensation, has a 0.5 meter steady state offset with a standard deviation of 17.7 cm, which is twice that of the controller that used disturbance compensation.

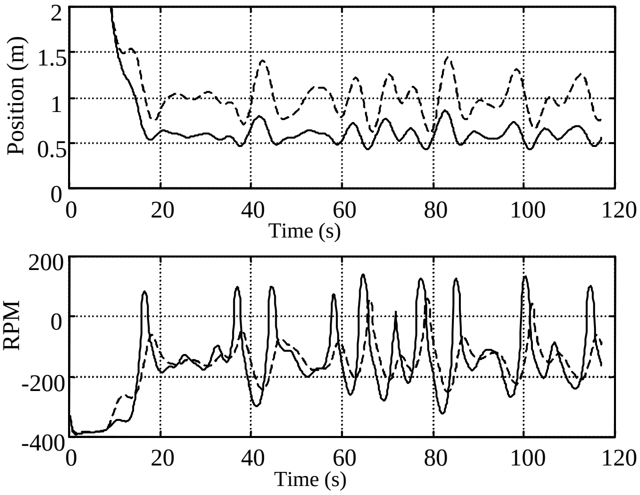


Fig. 5 Vehicle Response Comparison With and Without Disturbance Compensation, upper plot vehicle position with (solid line) and without (dashed line) disturbance compensation , and lower plot propeller RPM with (solid line) and without (dashed line) disturbance.

VII. CONCLUSIONS

The results presented in this paper demonstrate that using vehicle borne sensors, the mean direction of the seaway may be determined and used as an input to the mission controller for heading corrections. We have shown, through simulation, that a Kalman based, fusion filter coupled with a disturbance embodied sliding mode controller provides an AUV the ability to operate in the highly energetic shallow water environment and accurately stationkeep.

There are several open issues in need of further research and analysis. First, with recent improvements to the longitudinal surge model involving a thrust reduction term $gu_r|n|$, [6] and [10], the question must be answered as to how best to incorporate this term in the sliding mode control design. The ability to properly model and incorporate this term will increase the accuracy to which a vehicle can maintain position.

Second, further analysis must be accomplished on the sensor noise and uncertainty problem. With sensors operating at different sampling rates, and with different noise and uncertainty characteristics the issues involved with latency of data, and the stability issues associated with varying signal-to-noise ratios must be investigated.

Lastly, implementation of the filter/controller into the NPS PHOENIX AUV must be accomplished to test the ability of the controller to perform in the operational environment subject to the real world uncertainties.

ACKNOWLEDGEMENTS

The authors wish to thank Dr. Kam Ng of the Office of Naval Research for his financial support under contract number N0001496WR20037.

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